PAPER

Chemical Spill Characteristics in the San Diego Bay

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ABSTRACT

Dispersion of ocean pollutants in estuarine environments and bays (such as San Diego Bay) depends on the location of the source of the pollutants relative to the mouth and the tidal excursion, which is the net horizontal distance over which a pollutant particle moves during one tidal cycle of flood and ebb. Pollutant dispersion was investigated using a coupled hydrodynamic and chemical discharge model in this study. The results show the existence of two distinct (northern and southern) spill patterns of pollutant dispersion. The northern spill pattern is characterized by fast reduction of the pollutant concentration in the water column, rapid dispersion of pollutants to the San Diego port and to outside of the San Diego Bay, and slow dispersion of pollutants to the southern bay. The southern spill pattern is characterized by slow reduction of the pollutant concentration in the water column, slow dispersion, and confinement of pollutants in the southern San Diego Bay. The results may be useful for ocean pollution control and management.
Keywords: Two chemical spill patterns, San Diego Bay, ocean pollution, water quality management, chemical dispersion

1. Introduction

The San Diego Bay, located at the west coast of southern California, connects to the Pacific Ocean through a single channel at the mouth (Figure 1). It is a semienclosed bay and a natural harbor sheltered by overlapping peninsulas (in the west, Point Loma, and in the east, Coronado). The bay has been intensively engineered to accommodate shipping activities. Ninety percent of all available marsh lands and 50% of all available intertidal lands have been reclaimed, and dredging activities within the bay have been equally extensive (Peeling, 1975). The shoreline of San Diego Bay is spotted with high pollution from shipbuilding and ship repair facilities. The body of water in the bay is particularly at risk because of the military and industrial activities in and around it. Investigation of the dispersion of floating chemicals, such as benzene, is very important for the monitoring and control of water quality.

The San Diego Bay has a "flipped Γ" shape and is nearly 25 km long and 1–4 km wide (Figure 1a). The bottom topography of the bay is not homogeneous, with an average depth of 6.5 m. The northern/outer part of the bay is narrower (1–2 km wide) and deeper (reaching a depth of 15 m), and the southern/inner part is wider (2–4 km wide) and shallower (depth less than 5 m) (Figure 1b). Once pollutants are released into the San Diego Bay, dispersion of pollutants depends upon the hydrodynamic forcing caused by exchange between the San Diego Bay and the Pacific Ocean through a single north-south channel, which is about 1.2 km wide, bounded by Point Loma to the west and Zuniga jetty to the east, with depths between 5 and 15 m. The west side of the channel is shallower than the east side. Such topographic features cause a phenomenon called "tidal pumping," due to the asymmetry between the flow during the ebb and flood tides (Fischer et al., 1979). Transport time for pollutant particles moving out of the bay depends on the horizontal distance relative to the mouth and the tidal excursion, which is the net horizontal distance over which a water particle moves during one tidal cycle of flood and ebb. Numerical modeling and chemical/isotopic tracer analyses are generally used to investigate such dependence for water quality control and management. Between them, numerical modeling is cost-effective without affecting the water environment. Here, a numerical modeling study is presented. The model has hydrodynamic and chemical discharge components. The hydrodynamic part is driven by tides and winds and predicts the velocity field. The chemical discharge part is driven by the velocity field from the hydrodynamic model and predicts the pollutant dispersion.

2. Background

2.1. Vertically Well-Mixed Basin

The Space and Naval Warfare Systems Command (SPAWAR) deployed

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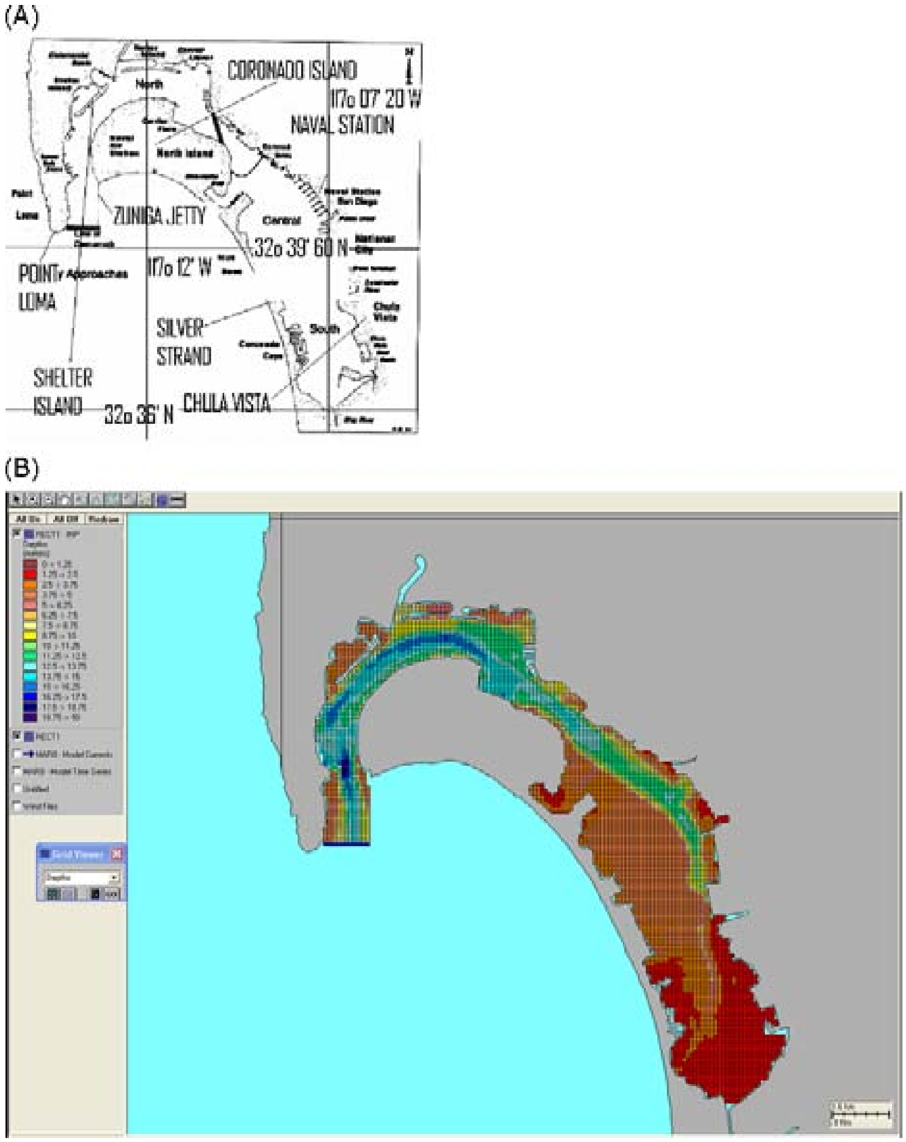
FIGURE 1

San Diego Bay: (a) main geographical locations and (b) bathymetry.



three acoustic Doppler current profilers (ADCPs) in the San Diego Bay in 1993 (Figure 2) with a broadband ADCP (station bb) located at the mouth of the bay (32°42′25.8″N, 117°13′30.6″W) from June 22 to July 23, and two narrowband ADCPs inside the bay: station nb1 located at (32°′43.98″N, 117°12′55.68″W) from June 22 to August 26 and station nb2 located at (32°42′17.22″N, 117°10′8.88″W) from June 23 to August 27. Figure 3 shows time series of horizontal velocity components (u, v) at three different depths (surface, middepth, and bottom) of two ADCP stations (nb1 and nb2) inside the bay. The three curves are very close together for each component (u or v) at each station (nb1 or nb2), showing well-mixed characteristics. The correlation coefficient between the surface and bottom currents is 97.2% for the u component and 96.3% for the v component at station nb1 and 92.0% for the u component and 94.7% for the v component at station nb2.

2.2. Atmospheric Conditions

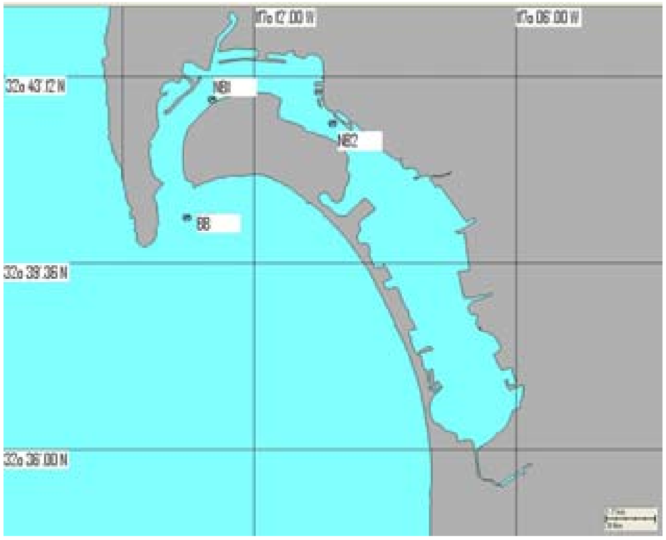
From National Oceanic and Atmospheric Administration's (NOAA) weather description, wind forcing is always less significant than tidal forcing in the San Diego Bay. The mean westerly winds in the afternoon and mean easterly winds in the evening and morning are less than 5 m/s with practically no storms in June, July, and August. Rain occurs mostly in winter and almost never in summer, with an annual precipitation of about 0.26 m. In terms of estuarine classification, the San Diego Bay is generally positive, i.e., drainage inflow exceeds evaporation (Pritchard, 1952). However, during the summer, the evaporation rate (about 0.16 m) exceeds precipitation (near zero) (Peeling, 1975), and a "reversed estuary" phenomenon is observed (Defant, 1961). Small water mass flux at the surface (mostly in winter) and weak wind forcing make the San Diego Bay a tidally driven basin (Fagherazzi et al., 2003).

2.3. Water Quality

Military and civilian vessel activities provide sources of the toxicity. Widespread toxicity in the San Diego Bay sediments contains copper, zinc, mercury, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and chlordane. No single chemical or chemical group has a dominant role in contributing to the identified toxicity. The semienclosed Shelter Island Yacht Basin (a boat harbor) has been added to California's list of impaired water bodies. The toxicity comes from specially formulated paints that are impregnated with biocides and applied to boat hulls to retard the

FIGURE 2

Location of the ADCP stations deployed by SPAWAR in June to August 1993. Note that station bb is located at the mouth of the San Diego Bay.

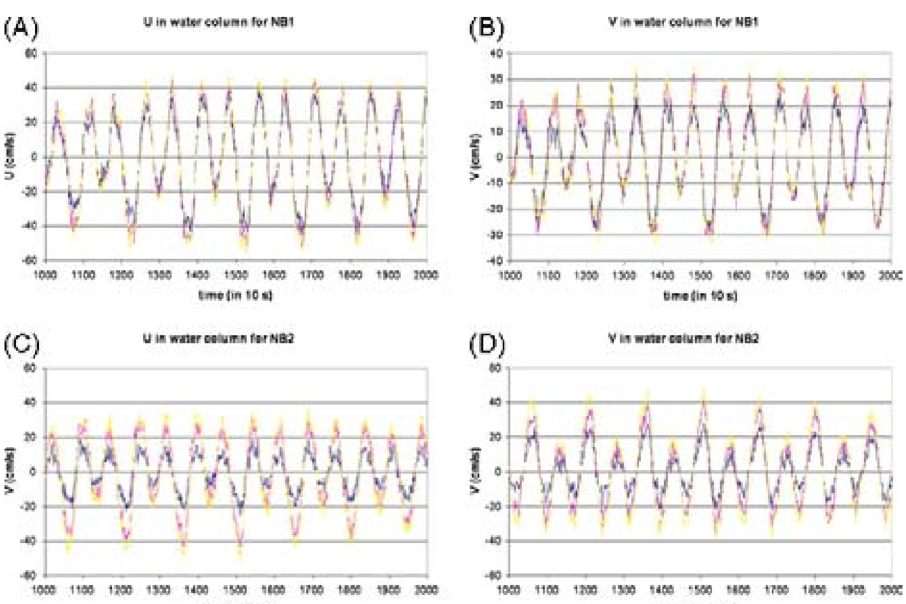


growth of fouling organisms such as barnacles.

In the current environment of threats to homeland security and as a big city waterway that hosts large U.S. naval bases, the San Diego Bay is a possible target of chemical attack with many possible chemical compounds. For example, benzene is an organic chemical compound with the molecular formula C_6H_6. It is sometimes abbreviated Ph-H. Benzene is a colorless and highly flammable liquid with a sweet smell, an aromatic hydrocarbon and the second [*n*]-annulene ([6]-annulene), and a cyclic hydrocarbon with a continuous pi bond. It is also related to the functional group arene, which is a generalized structure of benzene. Here, we use benzene as an example to show the effect of tidal pumping on the chemical spill patterns in the San Diego Bay. Sewage runoff is important but not included in this study.

FIGURE 3

Time series of (u, v) components from station nb1 at surface (yellow), middle depth (purple), and bottom (blue) for station nb1 (top) and nb2 (bottom): (a) u component and (b) v component. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2011/00000045/00000002.)



3. Hydrodynamic Chemical Discharge Model

3.1. Water Quality Management and Analysis Package

Water Quality Management and Analysis Package (WQMAP) is a numerical hydrodynamic model developed at Applied Science Associates, Inc. (ASA) with fitted boundaries (Muin and Spaulding, 1996, 1997). The model is configured to run in a vertically averaged (barotropic) mode or as a fully three-dimensional (baroclinic) mode. Several assumptions are made in the model formulation, including hydrostatic approximation, Boussinesq approximation, and incompressibility. In this study, the two-dimensional version is used.

WQMAP was implemented for the San Diego Bay, covering an area of 43 km^2. The computational mesh has 150 × 200 (30,000) grid nodes with an average horizontal resolution of 40 m. The sources for the water depths are the NOAA sounding data and navigation charts and the navy-conducted bathymetry survey. The navy data shows that the water depths in regions near the bay entrance are

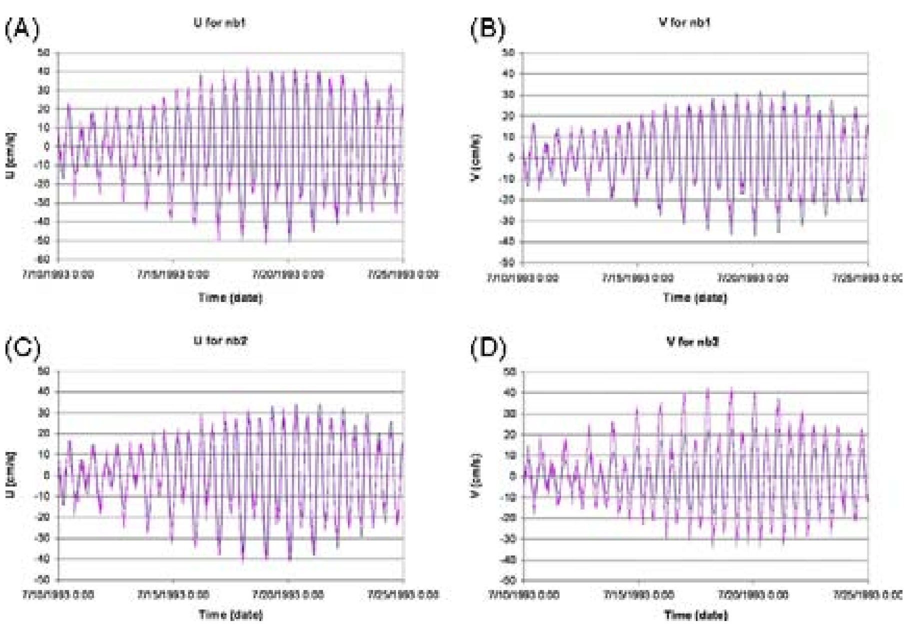
significantly deeper than the water depths shown on the NOAA navigation chart (Wang et al., 1998). The most up-to-date bathymetry data are used in the model.

The model was span up from a quiescent initial condition and uniform temperature (16°C) and salinity (34 ppt) for 1 day and then integrated with tidal and wind forcing from time 00:00 on 22 June 1993 to 23:54 on 27 August 1993 with time step of 6 min. The CFL condition is satisfied at this time step. Sea surface elevation at the mouth of San Diego Bay is available every 6 min at the NOAA Station 9410170, located at (32°42′48″N, 117°10′24″W) and taken as the tidal forcing function. The integration period is selected from 22 June 1993 to 27 August 1993 (see Figure 3) in accordance with the observational period of three ADCPs for model-data intercomparison.

Statistical analysis (Chu et al., 2001) shows good correlation between modeled and observed horizontal velocity with the correlation coefficients above 0.90 in all cases. At nb1, the correlation coefficient of the *u* component is 0.92. The observational *u* component ranges between −51.8 and 44.5 cm/s, and the modeled *u* component changes between −46.9 and 40.8 cm/s (Figure 4). The correlation coefficient of the *v* component is also 0.92. The observational *v* component ranges between −31.6 and 29.6 cm/s, and the modeled *v* component changes between −37.0 and 32.0 cm/s. Overall, the model velocities are reasonably good, especially taking into account that the data and the model output are not at exactly the same geographic location and the proximity of the ADCPs to shore. If finer grid and more accurate bathymetry are used, the model results may be further improved.

FIGURE 4

Model (blue curve) and (ADCP) data (purple curve) comparison for station nb1 (top) and nb2 (bottom): (a) *u* component and (b) *v* component. (Color versions of figures available online at: (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2011/00000045/00000002.)



3.2. Chemical Discharge Model

A chemical discharge model (called CHEMMAP) was also developed at ASA to predict or to simulate surface and subsurface spills, slick spreading, transport of floating, dissolved and particulate materials, evaporation and volatilization, dissolution and adsorption, sedimentation, and degradation. The model inputs are density, viscosity, vapor pressure, surface tension, water solubility, environmental degradation rates, and adsorbed/dissolved partitioning coefficients. The model outputs are the trajectory and fate of floating, sinking, evaporating, soluble/insoluble chemicals, and estimation of the distribution of chemical elements (mass or concentration) on the surface, in the water column, and in the sediments. The model separately tracks surface slicks, entrained droplets or particles of pure chemical, chemical adsorbed to suspended particulates, and dissolved chemicals (McCay and Isaji, 2002). More specifically, the model can predict the swept area by a floating chemical, as well as total, absorbed, dissolved, and particulate concentration in both the water column and sediments, and can determine the range and direction of contamination caused by the spill at a particular location.

4. Chemical Spill Patterns

Suppose that one barrel of a chemical (e.g., 10 tons of benzene) is released into the water from a small boat at 00:00 on day 1 at (1) northern San Diego Bay (32°43′N, 117° 13.05′W) (point 2 in Figure 1a) and (2) southern San Diego Bay (32°39′N, 117°07.92′W) (point 4 in Figure 1a). The release depth is 1 m, and the initial plum thickness is 0.5 m. Two distinct spill (northern and southern) patterns are found for all the chemicals. Here,

spill patterns of benzene are presented for illustration.

4.1. Northern Spill Pattern

After the pollutants are released at the northern San Diego Bay (32°43′N, 117°13.05′W), the pollutants disperse generally from the northern bay (north of 32°39′N) to outside of the San Diego Bay. They disperse very little into the southern bay (south of 32° 39′N). The benzene reaches the San Diego port (Figure 1a) in about 3 h. It transports outside of the San Diego Bay in 12 h (Figure 5). The southern bay is not contaminated for the first 5 days (Figure 6a) and weakly affected after 32 days (Figure 6b). Rapidly weakening of the pollutant concentration in the water column is found. The pollutant concentration is 20% after 5 days, reduces to 10% after 15 days, and reaches 4% after 30 days (Figure 7). There is plenty of time to take protective measures for the southern bay (Chula Vista area), where the impact of such an incident would be minor.

4.2. Southern Pattern

After the pollutants are released at southern San Diego Bay (32°39′N, 117°07.92′W), the spill pattern is totally different from the northern spill pattern. The pollutants disperse generally inside the bay with very few pollutants reaching the 32°41′N parallel. However, the naval station (Figure 1a) is affected within 12 h (Figure 8a) and completely contaminated in less than 3 days. It is important for protective measures to highlight this pattern because a chemical attack in the southern part of the bay would affect the naval station. After 17 days, the dissolved benzene reaches the San Diego port (Figure 8b). After 32 days, the dissolved benzene is confined in the southern San Diego Bay (Figure 9). It

FIGURE 5

Benzene dissolved concentration out of the bay 12 h after being dropped in the North San Diego Bay.

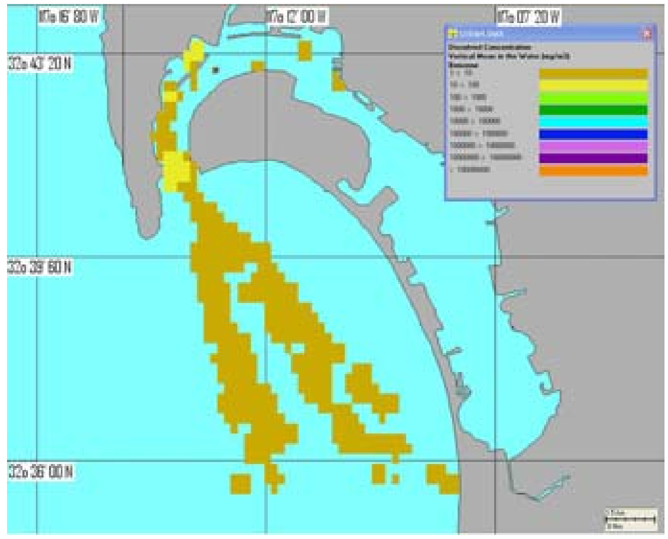


FIGURE 6

Dispersion of benzene (a) 5 days and (b) 32 days after being dropped in the North San Diego Bay.

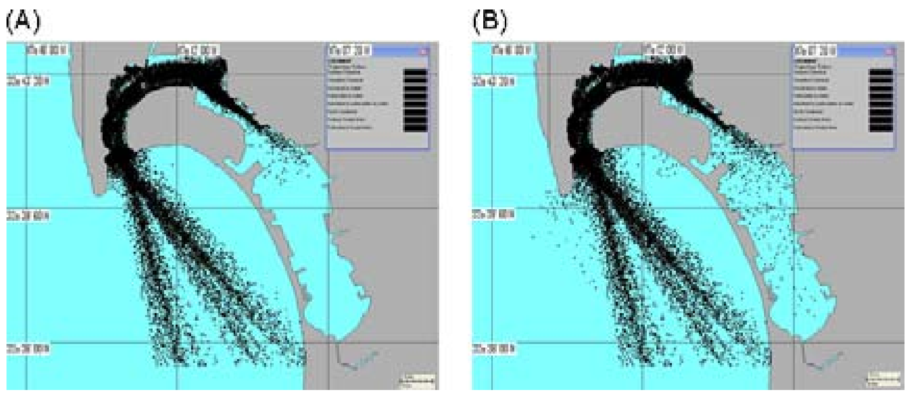


FIGURE 7

Mass balance for benzene dropped in the northern San Diego Bay.

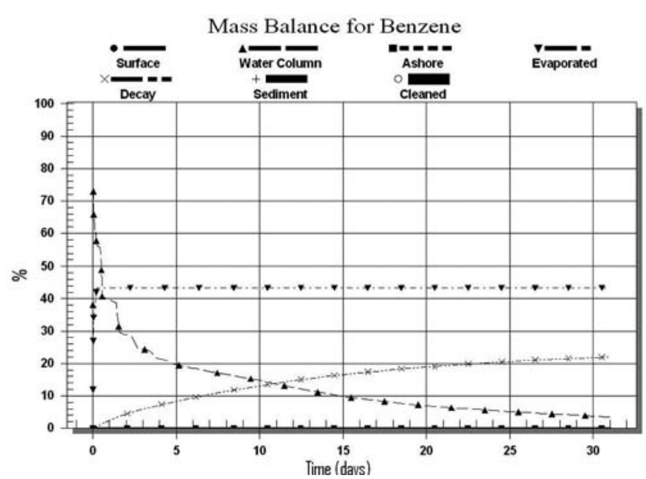


FIGURE 8

Benzene concentration (a) 12 h and (b) 17 days after being dropped in the South San Diego Bay.

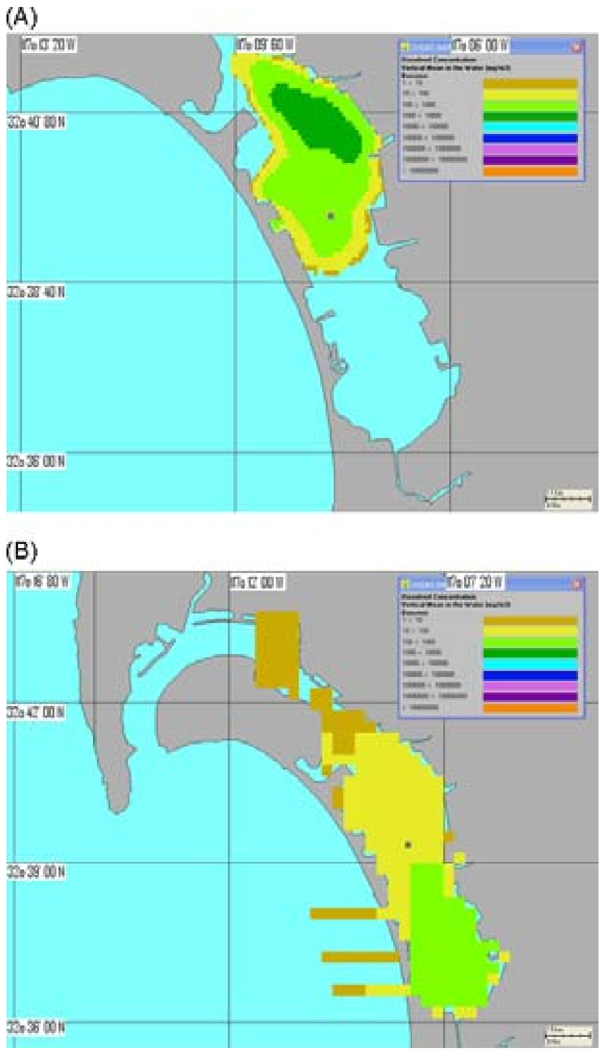
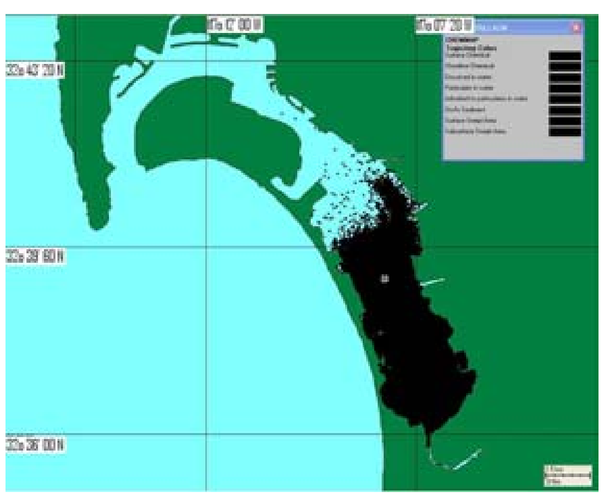


FIGURE 9

Dispersion of benzene 32 days after being dropped in the southern San Diego Bay.



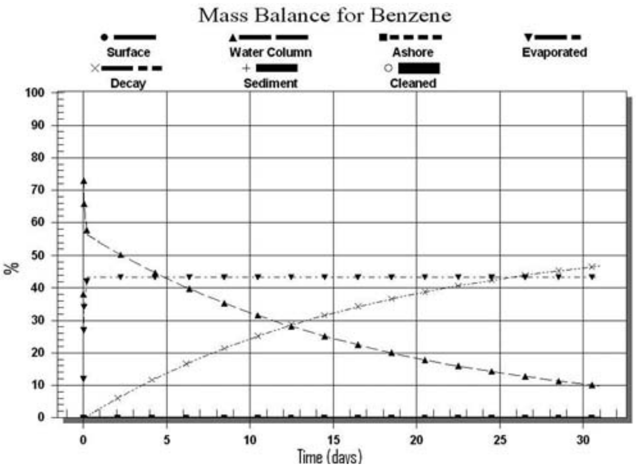
clearly shows that the pollutants are more likely confined in the southern San Diego Bay for quite a long period. Temporal variability of the pollutant concentration in the water column is quite different between the southern (Figure 10) and northern (Figure 7) spill patterns. Slow reduction of the pollutant concentration in the water column is found for the southern spill pattern. The pollutant concentration is more than 30% after 10 days, reduces to 25% after 15 days, and reaches 10% after 30 days (Figure10). This pattern may affect human beings and the environment as a result of the longer period of confinement of pollutants in the southern San Diego Bay.

5. Conclusions

In this study, two distinct (northern and southern) chemical spill patterns were found depending on the location of the pollutant source. The northern spill pattern occurs when the pollutants are released in the northern San Diego Bay. It is characterized by fast reduction of the pollutant concentration in the water column, rapid dispersion of pollutants to the San Diego port and to outside of the San Diego Bay, and slow dispersion of pollutants to the southern bay. The southern spill pattern appears when the pollutants are released in the southern San Diego Bay. The southern spill pattern is characterized by slow reduction of the pollutant concentration in the water column, slow dispersion, and confinement of pollutants in the southern San Diego Bay. Although the modeling results are useful, one should be precautious in applying them to ocean pollution monitoring, control, and management. This is due to uncertainties in the numerical model such as the bathymetry, discretization,

FIGURE 10

Mass balance for benzene dropped in the southern San Diego Bay.



boundary configuration, and forcing functions. Another problem is the lack of recent data for the San Diego Bay. The comparison was conducted between hydrodynamic model output and old ADCP observations because of the lack of more recent data. These issues need to be carefully considered before using these results.

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